TECHNIQUE FOR MEASURING INTERSUBBAND ELECTROLUMINESCENCE IN A QUANTUM CASCADE LASER

Government Contracts

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Technical Field

10 The present invention relates to the field of quantum cascade lasers and, more particularly, to the measurement and characterization of their intersubband electroluminescence.

Background of the Invention

15 As has been described extensively in the prior art (see, for example, F. Capasso et al., IEEE J. Select. *Topics in Quantum Electr.*, Vol.6 (6), p. 931-947 (2000)), a quantum cascade (QC) laser is based on intersubband transitions between excited states of coupled quantum wells, utilizing resonant tunneling as the pumping mechanism. Unlike all other semiconductor lasers (e.g., diode lasers), the wavelength of the laser emission of a QC laser is essentially determined by quantum confinement; i.e., by the thickness of the layers of the active region material. As such, it can be tailored over a very wide range without modifying the semiconductor material itself. For example, QC lasers with AlInAs/GaInAs active regions have operated at mid-infrared wavelengths in the 3 to 24µm range. In diode lasers, in contrast, the bandgap of the active region is the main factor in determining the lasing wavelength.

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More specifically, diode lasers, including quantum well lasers, rely on transitions between energy bands in which conduction band electrons and valence band holes, injected into the active region through a forward-biased p-n junction, radiatively recombine across the bandgap. Thus, as noted above, the bandgap essentially determines

30 the lasing wavelength. In contrast, the QC laser relies on only one type of carrier; i.e., it

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is a unipolar semiconductor laser in which electronic transitions between conduction band states arise from size quantization in the active region heterostructure.

Even though QC lasers have been the subject of much research and study since their initial development in 1994, the nature of their electron distribution function is still

5   not well understood.   An article by M. Troccoli et al., *Applied Physics Letters*, 77,1088-1090 (2000), discusses the possibility of extracting the excited state electronic population from the intersubband (ISB) emission of QC electroluminescence structures. Unfortunately, ISB electro-luminescence (EL), the best experimental probe for this type of analysis, in practice cannot be measured above laser threshold, due to the large

10   intensity difference between laser emission and electroluminescence emission, as well as the lack of detectors with a large enough dynamic range.

Summary of the Invention

The present invention relates to a technique for measuring intersubband

15   electroluminescence (ISB-EL) above laser threshold which is accomplished by cleaving the laser stripe along its length and detecting the ISB spontaneous emission from the direction orthogonal to the axis of the optical cavity.

In particular, a QC laser is cleaved longitudinally (along the active region) and the laser facets are subsequently coated with a highly reflective material. A detector is

20   disposed to capture the spontaneous emission which will exit from the active region along the cleaved face. The detector will also measure the scattered laser emission, resulting from defects in the laser material or waveguide, thereby allowing for the determination of the threshold current density (J_{th}) of the device.

In one embodiment of the present invention, the laser stripe is cleaved along the

25   direction orthogonal to the laser facets and approximately in the middle of the waveguide, using a diamond tip device. The scattered nature of the light can be analyzed by its polarization; the ISB-EL emission is fully TM polarized, and laser light is unpolarized due to the scattering process.

Brief Description of the Drawings

Referring now to the drawings,

FIG. 1 contains a diagram of a longitudinally cleaved QC laser useful to perform the ISB-EL measurement in accordance with the present invention;

5   FIG. 2 is a scanning electron micrograph of an actual QC laser cleaved in accordance with the present invention to perform the ISB-EL measurement;

FIG. 3 contains an energy level band diagram of an exemplary QC laser, with the electron minibands being slightly shaded and the square moduli of the relevant wave functions illustrated;

10   FIG. 4 illustrates the sub-threshold and above-threshold spectra for an exemplary QC laser, measured at 10°K, in pulsed mode, with a threshold current of approximately 1.6A;

FIG. 5 is a graph of the peak emission intensities of the 2→1 and 4→1 transitions as a function of the injected current;

15   FIG. 6 illustrates the sub-threshold and above-threshold spectra for a different QC laser, with a threshold current of approximately 740mA; and

FIG. 7 illustrate the emission intensities below and above laser emission for the laser of FIG. 6, as a function of the injected current.

20   *Detailed Description*

As described above, intersubband electroluminescence (ISB-EL) is considered to be one of the best probe for extracting excited state electronic population information from a QC laser. However, due to the large intensity difference between laser emission and luminescence emission (and the lack of detectors with a sufficiently large dynamic range), it has heretofore been extremely difficult to collect information regarding the electroluminescence in particular during laser operation. In accordance with the present invention, it has been found that by cleaving a QC laser in the longitudinal direction along its active stripe and subsequently coating the laser facets with a highly reflective (HR) material, it is possible to detect the ISB spontaneous emission from a QC laser in a direction orthogonal to its laser axis.

FIG. 1 illustrates, in diagram form, an exemplary QC laser 10 that has been cleaved so as to be useful for ISB-EL measurement in accordance with the present invention. FIG. 2 is a scanning electron micrograph of an actual QC laser that has been subjected to this cleaving process. In one method of forming such a cleaved laser

5   structure, the semiconductor wafer is first processed into 50μm wide deep-etched stripes by optical contact lithography and wet chemical etching – both processes being well-known in the prior art. An exemplary waveguide stripe 12 is illustrated in device 10 of FIG. 1. A layer 14 of insulation, such as silicon nitride, is then deposited on waveguide stripe 12 and metallic contacts 16 and 18 are evaporated on top surface 20 and bottom

10   surface 22, respectively, of device 10.

After the formation of contacts 16 and 18, device 10 is cleaved along the direction orthogonal to laser facets 24 and 26, illustrated as cleaved face 28 in FIG. 1 and defined along the y-z plane of device 10. In a preferred embodiment, device 10 is cleaved in approximately the middle of waveguide stripe 12, where a diamond tip cleaving tool may

15   be used. Subsequently, laser facets 24 and 26 are cleaved and coated with a highly reflective material (for example, a layer of Ti/Au, with an underlayer of SiO_2 to prevent shorting).

In order to perform the ISB-EL measurement, the device 10 as shown in FIGs. 1 and 2 is then mounted on a supporting substrate (such as a copper block), wire bonded,

20   and placed in a cold-finger helium-flow cryostat for measurement purposes. When QC device 10 is biased, laser emission 30 will exit both facets 24 and 26 along active region 30 of device 10 in case no HR coating was applied; or will be largely blocked by the coating. In accordance with the present invention, the intersubband electroluminescence 32 will exit active region 30 along cleaved plane 28, as shown in FIG. 1.

25   Since spontaneous emission is isotropic and laser light is stimulated solely along the laser cavity, photons detected from cleaved plane 28 should ideally originate only from spontaneous emission and provide an accurate measurement of the ISB-EL activity in a QC laser. However, any imperfection in the structure will result in scattering laser photons such that a fraction of the laser light will also exit along cleaved plane 28.

30   Accordingly, a spatial filter exhibiting a low numerical aperture (of a few millimeters, for

example), can be located in front of the device and aids in lowering the intensity ratio of the detected laser light with respect to the electroluminescence. Additionally, the two emissions can be distinguished in terms of their polarization. More particularly, the laser light will be unpolarized, due to be being scattered, while the electroluminescence will be

5   fully TM polarized. An added benefit of the laterally cleaved structure of the present invention is that the scattered laser light can be separately analyzed and measured to determine the laser threshold current density J_{th} for the device. In fact, the capability to perform such a measurement has resulted in the finding that the process of laterally cleaving the QC laser structure does not increase the threshold current density for the

10   device and, in fact, a slight improvement in threshold current is observed, likely due to the reduced mirror losses attributed to the HR coatings on the laser facets.

FIG. 3 illustrates a schematic energy band diagram for an exemplary QC laser structure, where in this case the energy level separation between states 2 and 3 of upper miniband 50 (referring to FIG. 3, state 1 is defined as the top-most energy state of lower miniband 52) is 19 meV, well below the LO-phonon energy (E_{lo}), implying an increased

15   intersubband relaxation time $\tau_{3\to2}$ (i.e., "bottleneck" effect), due to suppression of electron-phonon scattering. In this region, $\tau_{3\to2}$ is determined by electron-electron scattering and by electrons with a large in-plane wavevector that possesses enough energy for the emission of LO phonons. The intersubband relaxation time $\tau_{3\to2}$ can become as

20   large as several picoseconds, depending on carrier density and temperature. Increased $\tau_{3\to2}$ (and almost equal values of the optical dipoles matrix elements for the energy state transitions $2\to1$ (z_{21} = 2.04nm) and $3\to1$ (z_{31} = 2.34nm) can be used to explain the multi-peaked subthreshold spectrum typically observed with this structure and, in particular, the above-gap laser action at the $3\to1$ transition.

25   FIG. 4 illustrates the results of the ISB-EL measurement, performed in accordance with the present invention, on a laterally cleaved QC laser having the energy band structure shown in FIG. 3. The spectra were obtained at various current levels, as shown, in pulsed condition (70 ns pulse width, 80kHz repetition rate), and at a sample temperature of 10°K. This particular device was found to have a threshold current (I_{th}) of

30   approximately 1.6A, and the broad, multi-peaked spontaneous emission is visible both

below and above threshold, as shown. The above threshold measurements have been heretofore virtually impossible to record from laser facet measurements. Thus, by virtue of using the laterally cleaved structure formed in accordance with the present invention, the spectra can be measured at a bias current as high as 1.75A, as shown.

5   FIG. 5 illustrates the peak emission intensities of the $2\rightarrow1$ and $4\rightarrow1$ transitions as a function of bias current. As shown, the emission intensities exhibit a constant increase of spontaneous emission both above and below threshold – contrary to the expectation for spontaneous emission in a lasing system. In principle, the onset of lasing action should lock the population difference between the inverted states (in this case, $n_3 - n_1$). Under

10   the assumption that state 1 is empty (which is frequently assumed for QC lasers), n_3 is therefore locked and any increase in current should cause an increase of the laser light, not the spontaneous emission. However, the observed increase in spontaneous emission from the structure of the present invention can be used to prove that the relaxation times are so slow that states 2 and 4 are almost decoupled from the lasing system (i.e., the $3\rightarrow1$

15   transition). In fact, the relation $n_2 = \tau_2\alpha J/e + (\tau_2/\tau_{32})n_3$ (which results from a simple rate equation argument, α being defined as the injection efficiency into level 2) implies that n_2 would also exhibit a partial "locking" behavior, unless $\tau_2<<\tau_{32}$. Therefore, the only channel effective for laser action (in particular, from the injection region into the upper miniband of the active region) is the one through state 3, while all the carriers injected in

20   levels 4 and 2 must contribute to spontaneous emission proportional to the injected carrier densities. Therefore, these electrons are lost to the laser process, a result heretofore not directly experimentally confirmed, without the inventive capability of directly measuring the ISB-EL emission from the laterally cleaved QC laser structure.

      This bottleneck effect between states 3 and 2 can be mitigated by modifying the

25   QC laser design to exhibit an energy separation E_{32} at the design field equal to the LO-phonon energy, and with an optimized dipole for the $2\rightarrow1$ transition. FIG. 6 illustrates the measured ISB-EL spectra for such a device, under both sub-threshold and above-threshold conditions. The $3\rightarrow1$ emission, as shown, is virtually non-existent for this device, demonstrating the improved efficiency in the relaxation rate between states 3 and

30   2 (as a result of coupling with the phonon field). This effect can also be partially

attributed to the optical dipoles matrix elements now being more concentrated in the 2→1 transition (z_{21} = 3.1nm) than in the 3→1 transition (z_{31} = 0.6nm).

FIG. 7 illustrates the spontaneous emission intensities at an energy immediately below (left panel) and above (right panel) the laser frequency as a function of injected current. Unlike the graph of FIG. 5, where the spontaneous emission continued to increase for increasing current values, the spontaneous emission for this particular QC laser structure moves closer to saturation as the current rises above the threshold value (I_{th} ≈ 740mA). The exhibition of the spontaneous emission approaching saturation is thus indicative of the fact that the majority of the additionally injected carriers are converted into laser light.